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Best Practices Guide: Benchmarking Energy Efficiency in Laboratories

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Best Practices Guide: Benchmarking Energy Efficiency in Laboratories

INTRODUCTION

Purpose and Audience

A wide spectrum of laboratory owners, ranging from universities to federal agencies, have explicit goals for energy efficiency and greenhouse gas reductions in their facilities. For example, new federal buildings and major renovations of existing buildings are to reduce fossil fuel-generated energy consumption by 90% in 2025, and 100% in 2030, compared with a 2003 baseline (FEMP n.d.). Minnesota SB2030 standard requires achieving an 80% reduction from the average building baseline for commercial, institutional, and industrial buildings (SB2030 n.d).

A laboratory—new or existing—is much more likely to meet energy efficiency goals if quantitative metrics and targets are explicitly specified and tracked over the life cycle of the building, from design through construction, commissioning, operations, and renovations. If efficiency targets are not explicitly and properly defined, any additional capital costs or design time associated with attaining higher efficiencies can be difficult to justify relative to other priorities.

The purpose of this guide is to provide guidance on how to specify and compute energy efficiency metrics and benchmarks for laboratories, at the whole-building as well as the system level. The information in this guide can be used to incorporate quantitative metrics and targets into new construction or retrofit of existing facilities. For information on strategies and technologies to achieve energy efficiency, the reader is referred to I^{2}SL resources, including technology best practice guides and case studies.

How to Use This Guide

First, read this introductory section and the benchmarking process section. Follow the process outlined in the benchmarking process section. After you identify and prioritize your metrics, read the content for the relevant metrics to identify required data, benchmark the metric, and identify potential actions. As such, it is not necessary to read through all the information in the metrics sections beforehand, although you may want to skim through the content when prioritizing your metrics.

Definitions

Metric: a unit of measure that can be used to assess a facility, system or component; e.g. W/sf lighting power density (LPD).

Benchmark: a particular value of a metric that denotes a level of performance; e.g. California Title 24-2019 [CEC 2018] allows an LPD of 1.0 W/sf for laboratory spaces. A benchmark could also be a percentile value of a cohort of peers, e.g., 25th percentile of site energy use intensity for a peer group.

Metrics Described in This Guide

Table 1 shows the list of high-priority metrics and their relevance for new construction and existing buildings. It includes whole-building and system-level metrics, with an emphasis on ventilation systems given their unique impact on laboratory energy use. Appendix A provides an expanded list of metrics.

In the following sections, each high-priority metric is described in further detail, including definitions, benchmarks, actions that can be inferred from the metric, and special considerations when using and interpreting the metric. The scope of the metrics described in this guide is limited to the energy performance of building systems in laboratories and selected operational parameters such as air change rates and fume hood sash management. The scope does not include a wider range of operational factors that impact energy use, such as management systems and practices.

Table 1

Metric: ● More Relevant ○ Less Relevant	New Construction	Existing Building
Whole Building		
Site energy use intensity (kBtu/sf/yr; kWh/sqm/yr)	●	●
Source energy use intensity (kBtu/sf/yr; kWh/sqm/yr)	●	●
Greenhouse gas intensity (lbs CO_2e/sf/yr; kg CO_2e/sq.m/yr)	●	●
Water use intensity (gal/sf/yr; l/sq.m/yr)	●	●
Ventilation System		
Minimum ventilation rate (volume) (ACH)	●	●
Minimum ventilation rate (area) (cfm/sf; l/s/sqm)	●	●
Airflow efficiency (W/cfm ; W/[l/s])	●	○
System pressure drop (in.w.g.; Pa)	●	○
Fume hood airflow ratio (-)	○	●
Cooling and Heating		
Cooling system efficiency (kW/ton; kWe/kWt)	●	●
Heating system efficiency (%)	●	●
Plug loads		
Laboratory peak plug load intensity (W/sf; W/sqm)	●	○
Laboratory average plug load intensity - measured (W/sf; W/sqm)	○	●
Lighting		
Installed laboratory lighting power density (W/sf; W/sqm)	●	○

Table 1. High-priority metrics and relevance for new construction and existing buildings.

Benchmarking Process

Figure 1 summarizes the benchmarking process, which applies to both new construction and existing buildings.

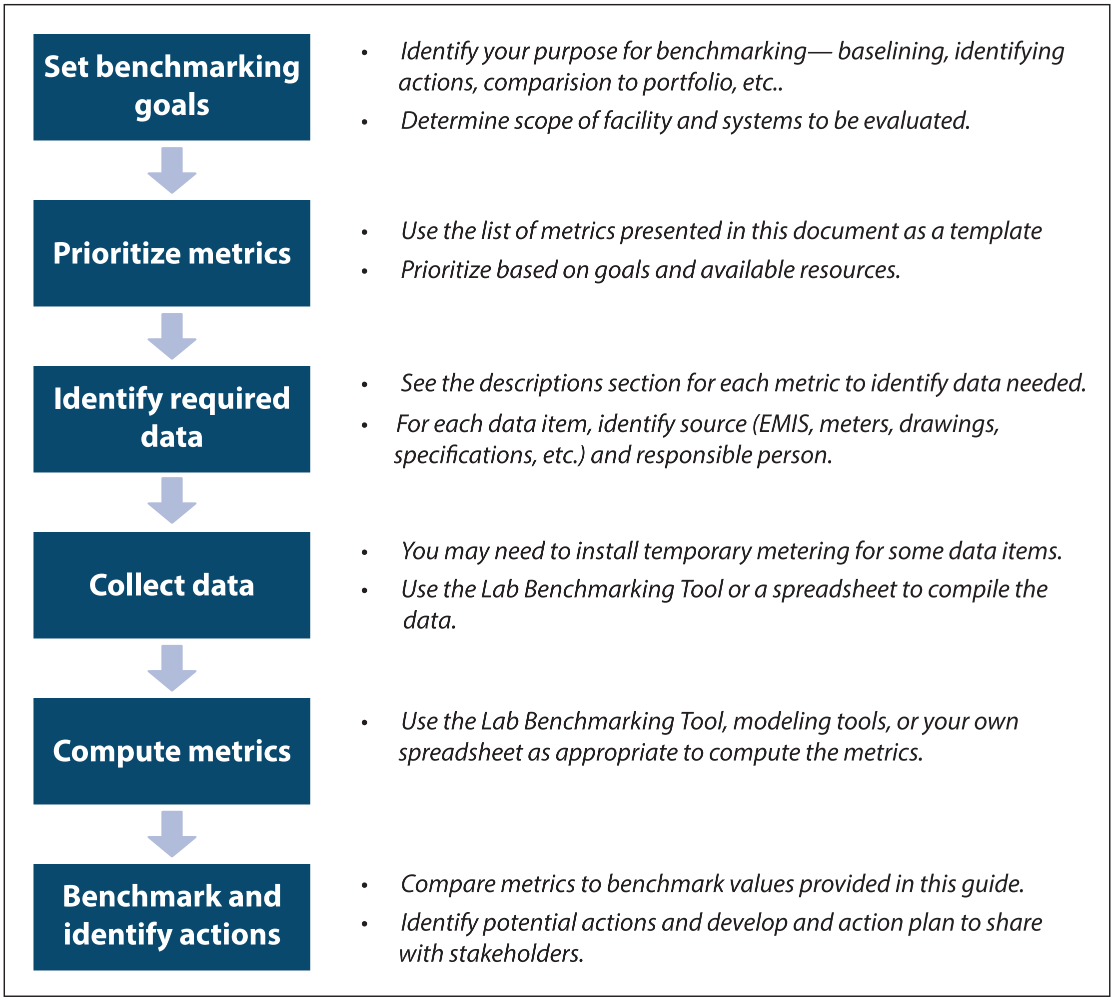


Figure 1. Goal-setting and prioritization of metrics are the first phases of the benchmarking process.

The following are some key considerations for an effective benchmarking process:

- **Identify metrics and set targets** with a stakeholder team. Metrics and targets are, in effect, key performance indicators (KPIs) for the quality of design and operation, and therefore should have the buy-in of all the key stakeholders (owners, designers, and operators). This could be done at project conception and refined during the early stages of the project. In the design for a new laboratory at Lawrence Berkeley National Laboratory, for example, a separate goal-setting meeting was held before design start, in which the designers and owners considered a wide range of metrics, selected key metrics, and set targets for each. The design team also identified a set of “secondary” metrics for which no explicit targets were set, but which would be tracked over the course of the design process. (The expanded list of metrics in Appendix A could be used as a template for identifying which metrics to track, and setting targets for them.)

- **Incorporate key metrics and targets in relevant organizational processes and documents.** Designers and operators are much more likely to ensure that targets are met if they are officially incorporated into the relevant documents and processes such as programming documents (for new construction) and regular management reports (for existing buildings).
- **Identify individual(s) responsible** for tracking metrics. For new construction, ideally the commissioning provider would assume overall responsibility on behalf of the owner, since metrics are integral to the performance tracking and assurance process. However, various design professionals may have responsibility for computing individual metrics and providing these to the commissioning provider (e.g., lab planner for plug load W/sf, HVAC engineer for airflow W/cfm, etc.). For existing buildings, ideally the energy manager or facilities manager would be responsible for continuous tracking and reporting.
- **Determine process and format** for tracking and documenting metrics. The Laboratory Benchmarking Tool (LBT) can be used to track metrics in a consistent manner over the course of a project. Alternatively, project teams may develop their own formats based on the LBT.

The Laboratory Benchmarking Tool

The Laboratory Benchmarking Tool (LBT) (I^2SL 2020) allows users to compare the energy performance of their building with that of similar facilities. The tool's peer group database contains data from more than 800 lab buildings in the U.S. Some of the key features of the tool include the following:

- In addition to whole-building metrics such as site and source EUI, the tool includes a number of system-level metrics such as ventilation rate, peak airflow intensity, cooling EUI, and plug load intensity. Benchmarking data are presented as histograms, scatterplots and summary statistics (Figure 2).
- Users can define a custom peer group by filtering the data set based on location, lab type, floor area, and various building and system characteristics.
- Users can import energy usage data from the ENERGY STAR Portfolio Manager tool, so they do not have to re-input the data into the LBT.
- An "Actionable Insights" module provides custom efficiency actions for each building using data provided by the user, helping to bridge the gap between benchmarking and action.

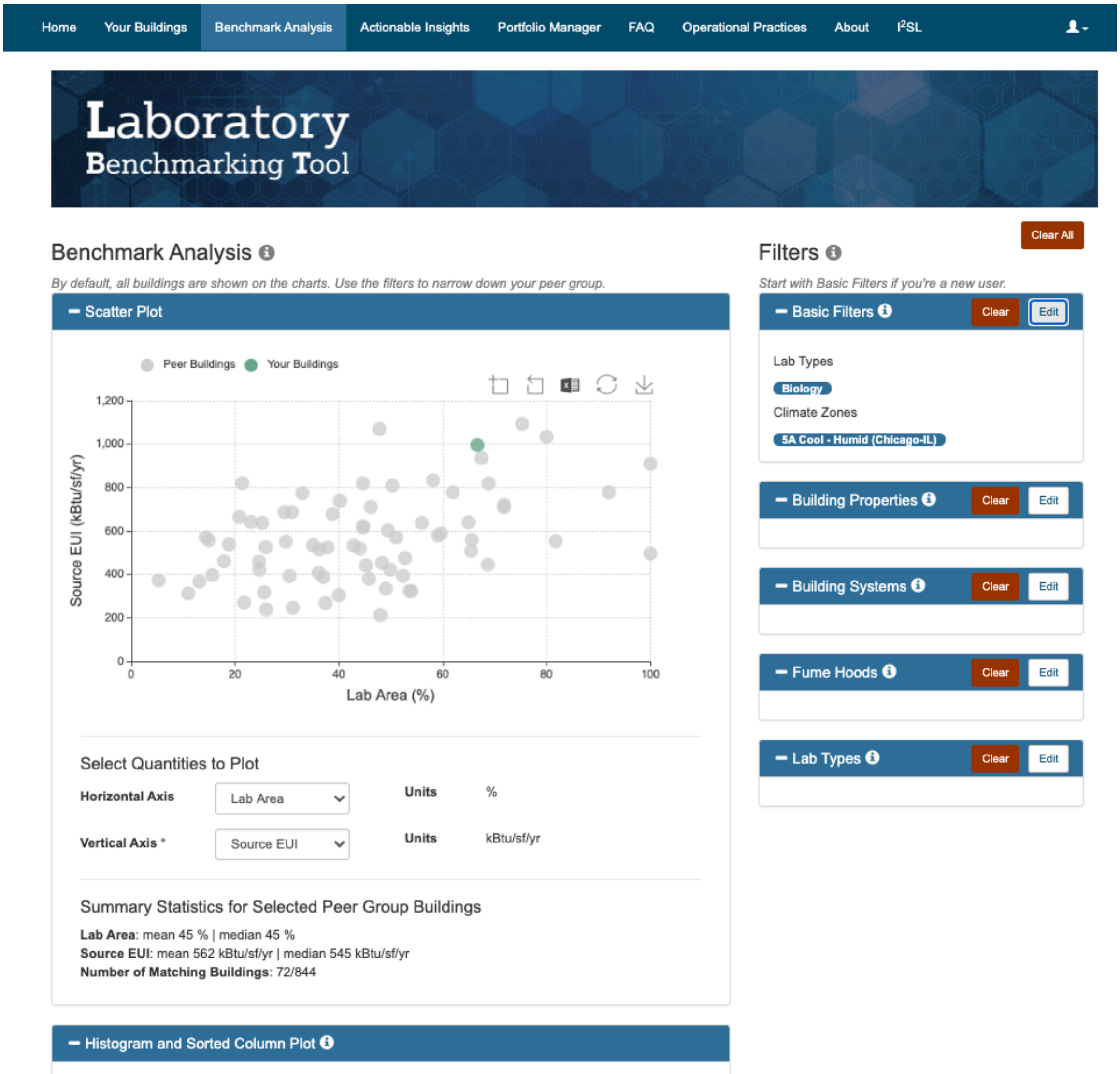


Figure 2. The Laboratory Benchmarking Tool analysis screen showing a scatterplot of source EUI vs. Lab area, and summary statistics. The panel on the right allows users to filter the data set using a host of building and system characteristics.

Whole-Building Metrics

Site Energy Use Intensity

Description

Site EUI is one of the most commonly used whole-building performance metrics, because the data required are usually easy to obtain from utility bills. Site EUI is the sum total of all energy delivered to the site per unit of gross building area. This includes grid-supplied electricity, natural gas, and other fuels, as well as district steam, and chilled and hot water. It does not include on-site energy generation from renewable sources. All energy streams should be converted to the same units.

Benchmarks
Broadly, there are two ways to define benchmarks: 1) relative to code, and 2) relative to a peer group. Code-based benchmarks are well-suited to new construction while peer benchmarking is best suited for existing buildings. We recommend the following benchmarks:

- Code-based benchmarks:
  - Standard practice: Meet ASHRAE 90.1-2019.
  - Good practice: 20% better than ASHRAE 90.1-2019.
  - Best practice: 40% better than ASHRAE 90.1-2019.
- Peer-based benchmarks are defined based on the percentile of the site EUI distribution of the peer group. Note that lower percentiles correspond to lower site EUI. The Laboratory Benchmarking Tool (LBT) can be used for peer benchmarking (Figure 3). Alternatively, users may also use their own portfolio if they have enough peer buildings to benchmark against.
  - Standard practice: 50th-25th percentile of peer group.
  - Good practice: 25th to 10th percentile of peer group.
  - Best: 10th or lower percentile of peer group.

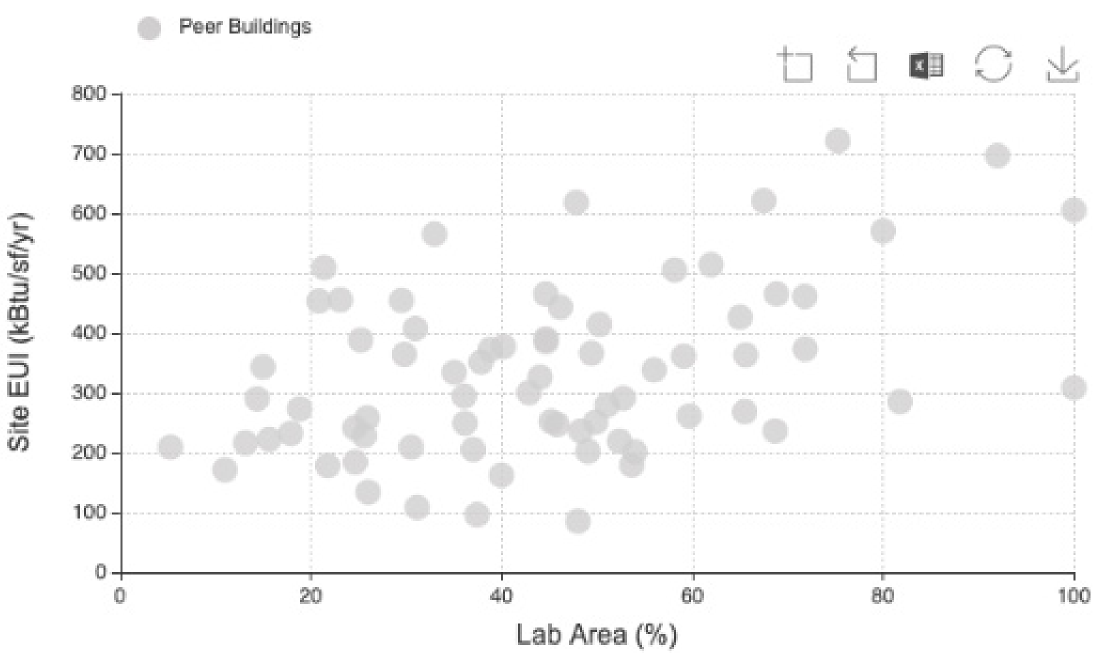


Figure 3. Example of peer benchmarking data from the LBT: Scatterplot of Site EUI vs. lab area for biology laboratory buildings located in the cool-humid climate zone (5A). Note the relationship between lab area % and site EUI. Also note the wide range in EUI even for buildings with similar lab area %.

Organizations with more aggressive energy efficiency goals may also consider zero net energy (ZNE) benchmarks such as the zEPI scale (NBI n.d.) and the Architecture2030 goals.

Figure 4. The University of Washington Life Sciences Building (designed by Perkins&Will) used ASHRAE 90.1-2007 as a benchmark during design, showing a 18% reduction in predicted site energy use. The buildings were also benchmarked against the LBT, showing a 59% reduction (153 kBtu/sf/yr vs. a baseline of 370 kBtu/sf/yr). Photo: Kevin Scott

Actions inferred

This metric does not in and of itself imply specific efficiency opportunities but rather provides a measure of overall efficiency potential (i.e., higher values relative to benchmark suggest higher efficiency potential and vice versa).

Special considerations

The effectiveness of peer benchmarking is limited by the degree to which the peer group of buildings has similar characteristics. While the LBT allows for simple data filtering of key characteristics (climate zone, lab area ratio, lab type, occupancy hours), there may be other characteristics (e.g., process loads) that cause energy use to be higher or lower independent of efficiency. Therefore, this metric is only a coarse screen for overall efficiency potential.

Comparison to a code baseline usually requires energy modeling, which always requires making a host of assumptions, either because some parameters are unknown, or because the modeling tool does not directly support certain building features. The following recommendations can help mitigate this issue:

- Use the I^{2}SL ASHRAE 90.1-2019 Appendix G Lab Modeling Guidelines (I^{2}SL 2020).
- Select experienced modelers. Energy modeling is a highly specialized skill, and owners and designers should select modelers that have experience with laboratories.

- Understand key assumptions. Modelers should document the key assumptions and review them with designers to ensure that they are valid.
- Test the sensitivity of key assumptions. Modelers should run parametric variations on the key assumptions and document the sensitivity of the results to variations in the assumptions.

A major advantage of code-based benchmarking is that it can normalize for context-specific factors such as occupancy hours and other programmatic elements. This is much more difficult to do with peer benchmarking due to the paucity of data.

Site EUI may not be as useful when comparing buildings with different energy sources, e.g., facilities served by district chilled and hot water vs. on-site chillers and boilers. In such cases, source EUI or GHG intensity would be a more effective alternative.

Source Energy Use Intensity

Description
Source EUI accounts for the primary energy used to generate and transport site-delivered energy (ENERGY STAR 2019). It is calculated by multiplying each site energy stream by an appropriate source energy factor. Table 2 (below) shows the source energy factors used in the ENERGY STAR Portfolio Manager tool, which represents the source energy factors for various delivered energy streams for buildings in the US and Canada.

Table 2

Energy Type	U.S. Ratio	Canadian Ratio
Electricity (grid purchase)	2.80	1.96
Electricity (on-site solar or wind, regardless of REC ownership)	1.00	1.00
Natural gas	1.05	1.01
Fuel oil (No. 1, 2, 4, 5, 6, diesel, kerosene)	1.01	1.01
Propane and liquid propane	1.01	1.04
Steam	1.20	1.33
Hot water	1.20	1.33
Chilled water	0.91	0.57
Wood	1.00	1.00
Coal/coke	1.00	1.00
Other	1.00	1.00

Table 2. Source-site ratios for Portfolio Manager energy types.

Benchmarks
Source EUI can be benchmarked exactly the same way as site EUI, i.e. relative to code or relative to a peer group (Figure 5). We recommend the same benchmarks as site EUI (see above).

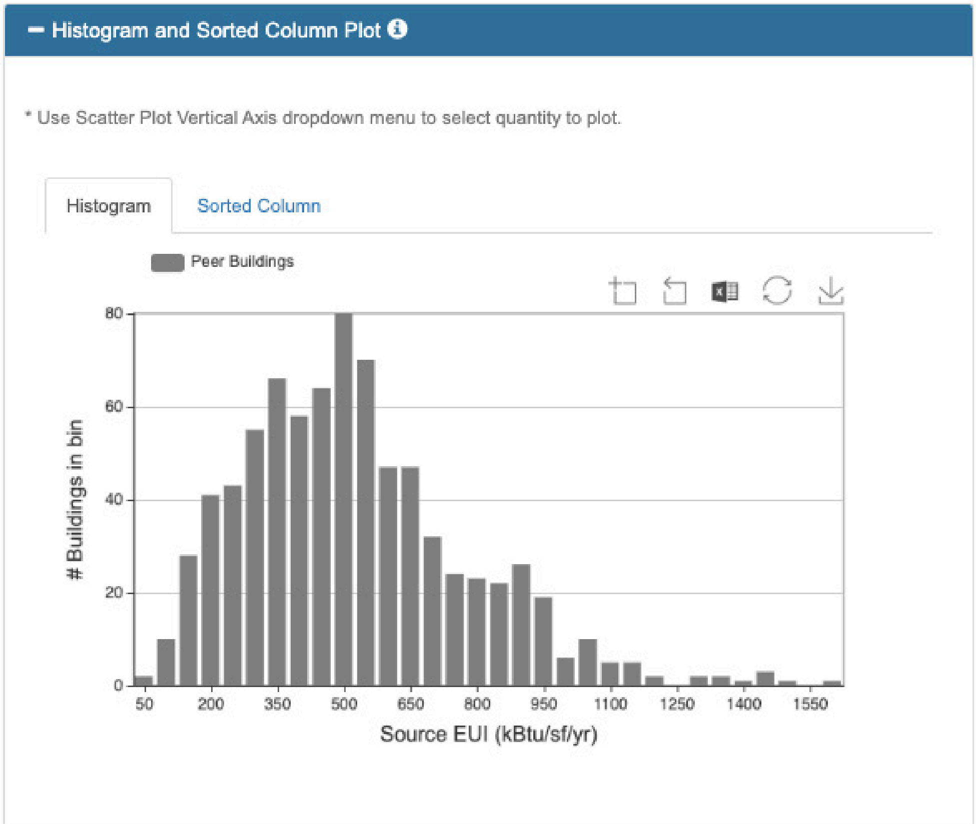


Figure 5. Histogram of source EUI for buildings in the LBT

Actions inferred

As in the case of site EUI, source EUI does not in and of itself imply specific efficiency opportunities but rather provides a measure of overall efficiency potential (i.e., higher values relative to benchmark suggest higher efficiency potential and vice versa). The main added value of looking at source EUI is that it allows for a more equitable comparison of buildings with different energy sources.

Special considerations

The special considerations for site energy also apply here. Additionally, a key aspect is whether to use common source factors vs. site-specific source factors for peer buildings. Site-specific source factors allow a comparison of actual source energy. Using common source factors (e.g., U.S. national averages) allows different buildings to be compared without accounting for differences in energy generation and transmission in their specific location (which is not in the control of individual building owners and operators).

Greenhouse Gas (GHG) Intensity

Description

GHG intensity (GHGI) is an increasingly important metric for organizations that have explicit climate goals and climate action plans. Indeed, for some organizations this has become the primary metric, superseding site and source EUI. GHG intensity typically accounts for all energy delivered and used on site. It is calculated by multiplying each site energy stream by an appropriate GHG emission factor.

Benchmarks
Since GHG is derived from site EUI, it can be benchmarked in a similar manner, i.e., relative to code and relative to peers (see again the site EUI section for more details). In addition, many organizations set GHGI reduction targets relative to a baseline. For example, the University of Toronto has committed to reducing GHG levels to 37% below 1990 levels by 2030. This applies to all new buildings and renovations, and the university then developed GHGI benchmarks for each building type. Table 3 shows the GHGI benchmarks for dry and wet labs.

Table 3

Metric	2020-2022 Targets		2022-2026 Targets		2022-2026 Targets	
	Wet Lab	Dry Lab	Wet Lab	Dry Lab	Wet Lab	Dry Lab
GHG Intensity – DES* (kg CO_2e/sqm)	50	16	50	15	12	12
GHG Intensity - Non-DES* (kg CO_2e/sqm)	30	11	30	10	8	8

* *DES: District energy systems*

Table 3. Example of GHGI benchmarks for dry and wet labs. Source: University of Toronto

Actions inferred
As in the case of site EUI and source EUI, GHGI does not in and of itself imply specific efficiency opportunities but rather provides an important means to set targets and track reduction in GHG emissions to meet climate goals.

Special considerations
Building-level GHG intensity usually includes only “scope 1” emissions (i.e., emissions from energy delivered to and used on site).

Water Use Intensity

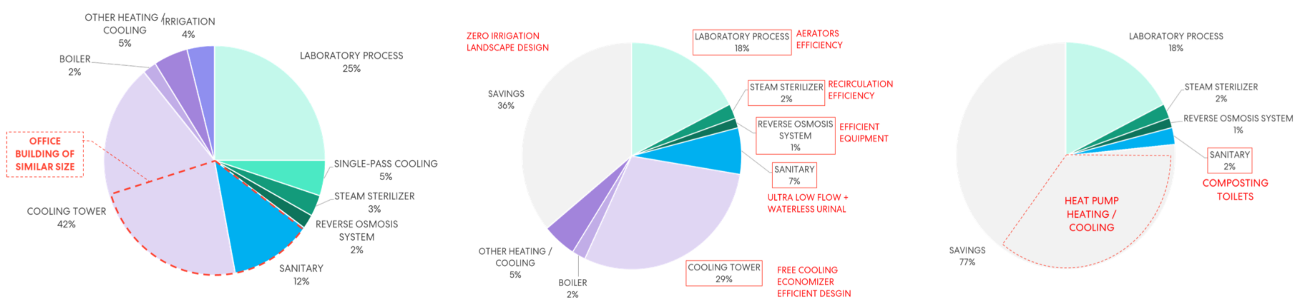
Description
Water use intensity is defined as the total water use on site per unit gross floor area. This includes all potable water delivered and used on site, including potable water used for HVAC systems, process water, landscape irrigation, and other uses. It does not include rainwater or other non-potable sources such as wells on site.

Benchmarks
Unfortunately there are not adequate data at this point to be able to set peer-based quantitative benchmarks for overall water use intensity[1]. Organizations with a large number of laboratories could conduct benchmarking across their portfolio and screen buildings with higher water intensity. For new construction, consider using the benchmarks in LEED BD+C. For existing buildings, consider setting a reduction goal as a percentage relative to current usage.

[1]*However, LEED has benchmarks for water-consuming fixtures and equipment.*

Actions inferred

Major opportunities to reduce water use in laboratories include laboratory equipment such as reverse-osmosis (RO) water purifiers and steam sterilizers, as well as cooling towers and bathroom fixtures as in other building types. Reducing HVAC energy use is also a major way to reduce water use. Where applicable, landscape irrigation is a significant opportunity to reduce potable water use, by using recycled water. See the Labs21 water efficiency guide (Tanner 2005) and EPA Water Sense and Work (EPA 2012) for more information.



Typical Lab

All uses fed via
potable city water or well water

TYPICAL LAB DATA: WATERSENSE AT WORK, US EPA, 2017

HP BLDG + Lab Eff

Lab and Potable fed via
potable city water or well water

Mechanical uses fed via
non-potable graywater
from rain catchment and/or
reclaim (RO, condensate, etc)

Net Zero Water

All uses fed via
non-potable graywater
from rain catchment
or from reclaim of other uses

Figure 6. Water efficiency concepts. Source: Perkins & Will

Special considerations

Landscape irrigation can significantly skew comparisons with buildings that do not have this use. Consider separately metering water used for irrigation.

This metric is limited to potable water. Sites that use well water or other sources may also want to track those sources separately or use a combined total water use metric (See Appendix A for an expanded list of metrics.)

Ventilation System Metrics

Minimum Ventilation Rate

Description
For most laboratory spaces, there is a minimum ventilation rate prescribed by EHS personnel, based on codes and standards. The basis of design is usually stated as air changes per hour (ACH). The minimum ventilation rate is often the driver of overall lab airflow rate. In some cases, minimum laboratory ventilation may be driven by other factors, such as thermal loads (for labs with excellent laboratory ventilation management practices or labs in extreme climates), high fume hood density (typically greater than 1 sf of hood work surface per 25 sf of laboratory), or extraordinary technical requirements (cleanrooms, unusual temperature or humidity stability, etc.). Laboratory owners should conduct a Laboratory Ventilation Risk Assessment (LVRA) to establish ventilation appropriate to the laboratory activities.

It is important to consider differences in laboratory activities and risks when benchmarking minimum ventilation rates. For example, teaching laboratories often support a more limited set of activities than research laboratories within the same academic institution. A laboratory should establish air change rates for different laboratory spaces within a given building based on their risks, a process referred to as risk banding, rather than a single rate for the entire building.

Additionally, the level of hazard protection offered by a given air change rate depends on the pattern of airflow within the space. When setting ventilation rates, it is important to consider ventilation effectiveness as well as ventilation rate. This topic is covered in the I^{2}SL Smart Labs Toolkit.

Minimum ventilation rates can be benchmarked with two metrics:

- Air changes per hour (ACH): This is the most commonly used metric and is based on the volume of laboratory spaces.
- Airflow per unit floor area of lab space (cfm/sf): Some laboratory professionals contend that this is a more appropriate metric, given that laboratory hazards are more related to floor area than volume i.e. a laboratory with a high ceiling doesn’t inherently require more ventilation.

Benchmarks
Various standards and guidelines indicate that minimum ACH can vary between 4 and 12, which is a very wide range, while others state that prescriptive ventilation rates are not appropriate. Table 4 shows the range of values listed in various standards. Values higher than 6 ACH (when occupied) and 4 ACH (unoccupied) should be explicitly questioned and justified as being required for health & safety.

Table 4

Code/Standard		Occupied ACH	Unoccupied ACH	Comments
ACGIH		None specified	None specified	Based on specifics of the hazard and environment
IMC		6	1.7	
NFPA 45		6+	4	
NRC, Prudent Practices		6 to 12	None specified	
29 CFR 1910.1450, Appendix A		None specified	None specified	Continuous ventilation is appropriate
ANSI Z9.5		None specified	None specified	Ventilation rates depend on a number of concerns. References ASHRAE 62.1
ASHRAE 62.1		6	1.7	
ASHRAE Committee 9.10	LVDL-0	ASHRAE 62.1	ASHRAE 62.1	See Standard for definitions of each LVDL
	LVDL-1	ASHRAE 62.1	ASHRAE 62.1	
	LVDL-2	4 to 6	ASHRAE 62.1	
	LVDL-3	6+	4	
	LVDL-4	8+	4	

Table 4. Minimum air change rates recommended in various codes, guides and standards. Source: I²SL Smart Labs Toolkit

Actions inferred

The purpose of benchmarking minimum ventilation rates is to explore opportunities for optimization. Specifically, optimization in this context means reducing air change rates while maintaining or improving safety. The I²SL Smart Labs Toolkit (I²SL n.d.) offers detailed guidance on how to assess and optimize air change rate. Demand-controlled ventilation offers a significant opportunity to effectively reduce air change rates by directly measuring pollutant concentration levels and adjusting air change rates to meet pollutant thresholds.

Airflow Efficiency

Description

Ventilation airflow efficiency is one of the most significant ways that HVAC design engineers can influence overall lab efficiency. This metric is defined as the total power of supply and exhaust fans divided by the total supply airflow (W/cfm), using design values. It provides an overall measure of how efficiently air is moved through the laboratory, from inlet to exhaust, and takes into account low pressure drop design as well as fan system efficiency (motors, belts, drives).

Benchmarks
ASHRAE 90.1 defines current standard practice. Suggested benchmarks are:

- Standard practice: Meet ASHRAE 90.1-2019 Appendix G.
- Good practice: 10-20% below ASHRAE 90.1-2019 Appendix G.
- Better practice: Greater than 20% below ASHRAE 90.1-2019 Appendix G.

Note that ASHRAE 90.1 includes fan power adjustments for several context-specific factors relevant to laboratories.

Actions inferred
There are two major actions that can be taken to improve airflow efficiency:

- Reduce system pressure drop by removing or changing components (e.g., excessive/dirty filters, excessive sound attenuators). In new construction, it also includes duct sizing and AHU sizing. See the system pressure drop metric for more information.
- Improve fan system efficiency by retrofitting motors, belts, drives.
- Trend data for this metric can also help identify issues such as filter loading sequence-of-operations changes.

Special considerations
In some cases, installed fan power, heating capacity, and cooling capacity are sized to meet "emergency operation" criteria, which in terms of airflow can be 25% higher than "normal operation." In such cases, the "normal operation" mode should be used for calculating and benchmarking this metric.

System Pressure Drop

Description
This is the total design pressure drop for the supply and exhaust systems, usually expressed in inches of water gauge (in.wg). It is a key driver of overall airflow efficiency and therefore is worth benchmarking separately, especially for new construction where there are significant opportunities to reduce overall pressure drop.

Benchmarks
ASHRAE 90.1 defines current standard practice. Suggested benchmarks are:

- Standard practice: Meet ASHRAE 90.1-2019, after fan power adjustments.
- Good practice: 10-20% below 90.1-2019 after fan power adjustments.
- Better practice: Greater than 20% below 90.1-2019 after fan power adjustments.

Note that ASHRAE 90.1 includes pressure drop adjustments for several context-specific factors relevant to laboratories. Also note that the ASHRAE value is expressed in terms of fan system brake horsepower, which can be converted to total pressure drop based on the formula underneath table 6.5.3.1-1 in the Standard, i.e. total pressure drop = (5.37 + sum of pressure drop adjustments) in. w.g.

Actions inferred
Pressure drop can be reduced through appropriate duct layout (e.g., minimizing bends), increasing duct cross section, bypass of coils and energy recovery in air-handling units, removing excessive sound attenuators, and selecting low pressure drop filters, coils, connectors and other components.

Fume Hood Airflow Ratio

Description
Fume hood airflow management ratio is defined as the ratio of the average flow over a given time period (e.g., a day, week, or year) to the minimum flow over the same time period. Minimum flow is the flow through the fume hood when the sash is closed. For a typical 6-ft fume hood, this is usually about 250 cfm. A typical 6-ft fume hood with an 18-in. sash-stop operates at about 775 cfm. Therefore, if the sash were never closed, the airflow management ratio would be 3.1. If the sash were closed 50% of the time, the ratio would be 2.05.

This ratio can be calculated for a single fume hood or a collection of fume hoods. The metric may be calculated over any period of time, and this should be specified when documenting the metric.

Benchmarks
Given the wide variation in how fume hoods may be used, it may be difficult to compare this metric across peers, unless it is known that the usage of hoods is very similar. One approach is to develop a benchmark based on expected usage. For example, consider a fume hood that operates at 250 cfm when the sash is closed and 775 cfm when the sash is open; if the fume hood is assumed to be in active use (sash open) for 4 hours per day, the airflow management ratio with ideal sash management (i.e., sashes always closed when not in use) will be 1.35 i.e. $(250*20\div24 + 775*4\div24) \div 250$. If sashes were left open 8 hours/day (i.e., twice longer than than actually needed), the airflow management ratio would be 1.7, which could be considered a benchmark.

Actions inferred
A high value (e.g., greater than 2) may indicate opportunities for improving sash management. This can be done via behavior campaigns to improve user awareness and training as well as technology solutions such as vacancy-based automated sash closing.

A low value of the metric generally indicates good sash management. However, a value consistently close to 1 could indicate that the fume hood is barely used and may be a candidate for decommissioning.

Special Considerations
Note that this metric addresses the ratio of average to minimum flow. It does not directly address the setting for minimum flow itself. See the Smart Labs Toolkit for more information.

Cooling and Heating Metrics

The metrics and benchmarks to evaluate the efficiency of chiller and boiler systems in labs are not different than those typically used in other commercial buildings. The most important metrics are overall cooling system efficiency and overall heating system efficiency. While individual component metrics (chiller kW/ton, pump W/gpm, etc.) are useful for identifying more specific efficiency opportunities, they do not account for controls optimization, which can be especially pertinent in laboratory facilities with irregular part-load profiles.

Cooling System Efficiency

Description
This metric characterizes the overall efficiency of the cooling system in terms of energy input per unit of cooling output. It should include chillers, primary and secondary pumps, and cooling towers. It can be calculated over any time period, but should ideally be calculated over the entire operational period of the system so that it covers the whole range of thermal demand and outdoor weather conditions.

Benchmarks
The benchmarks will vary based on chiller type, size, and location. In general, around 0.70 kW/ton would represent the benchmark for best practice.

Actions inferred
Many efficiency actions are available to improve the overall efficiency of the chiller plant. These include modularization, high-efficiency chillers, all-variable-speed systems, premium efficiency motors, increased chilled water temperature, water-side economizers, and controls optimization (staging, resets, etc.).

One additional factor for laboratories is turn-down ratio. Laboratory systems are often oversized due to reliability/redundancy requirements, over-estimated process loads, or other factors. Even when systems are “right-sized,” many hours of operation entail loads that are much lower than peak. Therefore, chiller systems in labs should be designed for low minimum turndown ratios, defined as the ratio of minimum load (with continuous compressor operation without hot gas bypass or other false loading methods) to design load. In the Molecular Foundry at Lawrence Berkeley National Laboratory, the chiller system is capable of a 5% turndown ratio. In labs with tight humidity control, even lower ratios are warranted, unless alternative dehumidification strategies are adopted.

Special considerations
Absorption chillers are typically evaluated using coefficient of performance. The efficiency of absorption chillers should not be compared to that of electric chillers unless the primary energy of fuel inputs is considered.

Heating System Efficiency

Description
This metric characterizes the overall efficiency of the heating system in terms of energy input per unit of heating output. It should include boilers and pumps. It can be calculated over any time period, but should ideally be calculated over the entire operational period of the system so that it covers the whole range of thermal demand and outdoor weather conditions.

Benchmarks
In general, 90% efficiency would represent the benchmark for best practice for boilers.

Actions inferred
There are many efficiency actions that can be used to improve the overall efficiency of the boiler plant. These include modularization, high efficiency boilers, lower hot water temperature, and controls optimization (staging, resets, etc.).

While not common, air-source heat pumps are also used in some laboratories, especially in milder climates.

Plug and Process Loads Metrics

Laboratory Peak Plug Load Intensity

Description
This is the peak equipment load per unit of net laboratory area. The values may vary across lab spaces in a given building. Note that the assumption for electrical system design is usually higher than that for HVAC system design. This metric refers to the plug load intensity used for HVAC design (generally the peak load based on a 15-min average, not the instantaneous peak that would be used for electrical system design).

Benchmarks
The benchmarks for this metric are driven by the type of processes and equipment in the laboratory. Figure 7 provides a range of measured values in various types of laboratories. These ranges are based on measurements in about 40 laboratories (Mathew 2007). Design values will necessarily include a factor of safety above measured plug loads, to account for unanticipated uses. The factor of safety should be determined and agreed to in consultation with the lab owner and users so that the design professionals do not select excessive factors of safety.

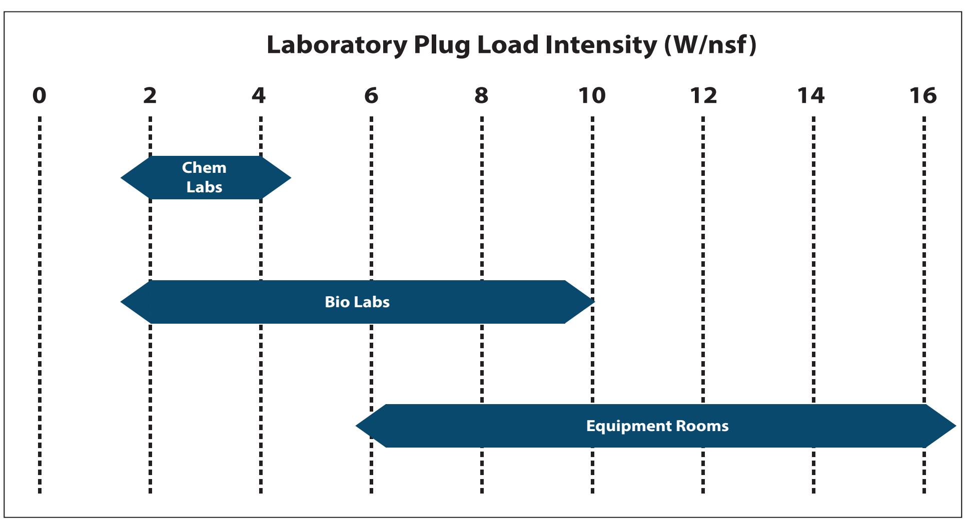


Figure 7. Range of peak plug loads measured in different types of laboratories

Actions inferred

Equipment loads in laboratories are frequently overestimated because designers often use estimates based on “nameplate” data, plus design assumptions of high utilization. This results in oversized HVAC systems, higher initial construction costs, and increased energy use due to inefficiencies at low part-load operation. Peak plug load intensity can be used to assess and compare designed and measured plug load intensity at comparable facilities. A high value for this metric indicates the opportunity to right-size HVAC systems and improve part-load efficiency. See the related I²SL guide for more information (Frenze et al. 2005). Designers may also consider a dedicated process cooling water loop for laboratory equipment heat rejection.

Laboratory Average Plug Load Intensity

Description

This is the average equipment load (or, equivalently, total energy use) per unit of net laboratory space. Measured average loads are typically much lower than peak design equipment loads. As an illustration, Figure 8 shows power density (W/sf) measurements in a variety of lab spaces in a building on the University of California, Irvine campus (Gudorf and Hartley 2013). The open lab spaces, which occupy most of that building’s lab area, have average equipment power density of less than 1 W/sf.

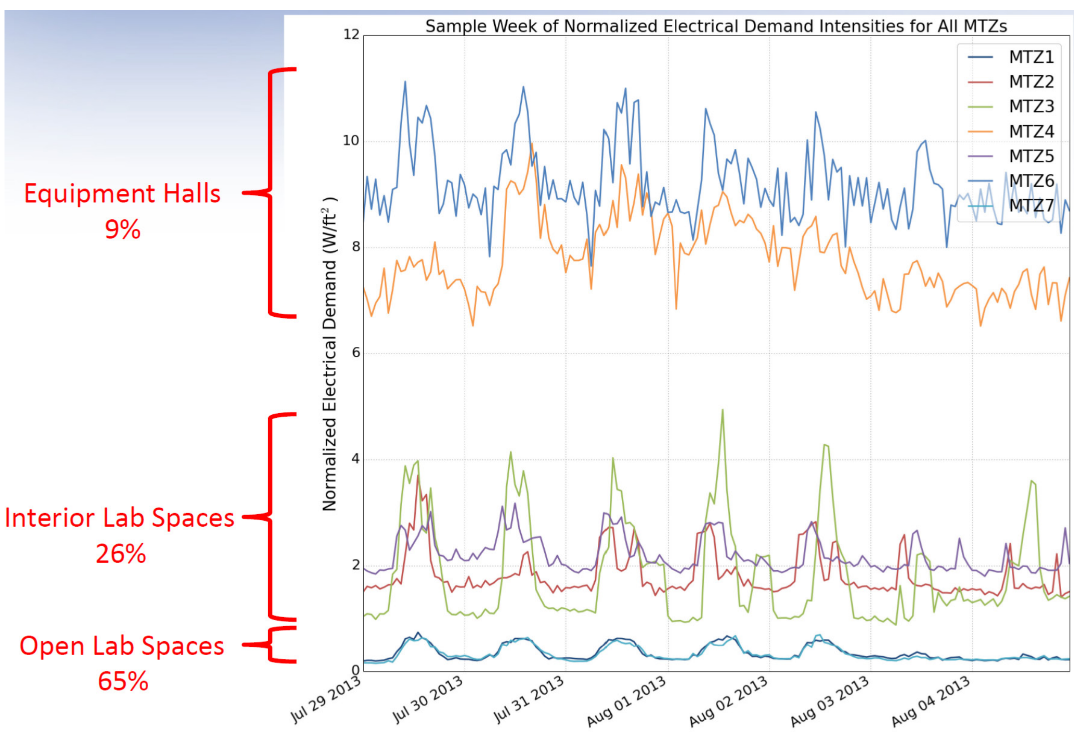


Figure 8. Plug load measurements in selected lab spaces at UC Irvine. Percentage values in red denote the fraction of lab area occupied by each space type. Source: Gudorf and Hartley 2013

Benchmarks
As with the peak equipment loads, the benchmarks for this metric are driven by the type of processes and equipment in the laboratory. Average equipment loads are also strongly driven by equipment usage patterns. Within a building or campus, the average equipment loads in lab spaces (or suites) with similar research purposes can be compared to identify spaces with unusually high average equipment loads.

Actions inferred
A high value for this metric may suggest the following actions:

- Conducting a usage audit to identify equipment that may be turned off when not in use, or permanently retired.
- Procuring equipment that is more energy efficient.
- Consolidating equipment in centralized shared facilities.

Lighting Metrics

Lighting accounts for a relatively small portion of lab energy use. The key metrics and benchmarks to evaluate the efficiency of lighting systems in labs are not fundamentally different than those typically used in other commercial buildings. These include daylight factors, illuminance levels, lamp and ballast efficacy, lighting power density, etc. We recommend one key metric for benchmarking: installed lighting power density.

Installed Laboratory Lighting Power Density

Description
This is defined as the installed lighting power per unit of net laboratory area.

Benchmarks
ASHRAE 90.1-2019 specifies a maximum of 1.11 W/sf for laboratory spaces in (or used as) a classroom, and 1.33 for all other laboratory spaces. California Title 24-2019 specifies a maximum value of 1.0 W/sf for scientific laboratory areas.

For new construction and lighting retrofits, 1.0 W/sf should be considered as a benchmark for standard practice. A good practice benchmark would be 20% lower than ASHRAE 90.1-2019, and best practice would be 30% below ASHRAE 90.1-2019.

Actions inferred
A high value for this metric indicates the opportunity to improve the lighting efficiency through more efficient lamps and ballasts, and more effective fixtures and lighting system configuration.

Conclusion

Laboratories are much more likely to meet energy efficiency and greenhouse gas goals if quantitative metrics and targets are explicitly identified and tracked during the course of design, delivery, and operation. This guide described key metrics and benchmarks at the whole-building level as well as at the system level.

- It is strongly recommended that whole-building targets be evaluated against empirical benchmarks that are based on the measured energy use of peer facilities.
- Key ventilation system metrics include: minimum air change rate (ACH, cfm/sf), ventilation airflow efficiency (W/cfm), system pressure drop, and fume hood airflow ratio.
- Heating, cooling, and lighting system efficiency metrics for laboratories are not significantly different from those used for other commercial buildings, although there are some special considerations for laboratories.
- Design assumptions for plug loads should be benchmarked against measured values in comparable laboratories.

Metrics and targets are in effect key performance indicators for the quality of design and operation, and therefore should have the buy-in of all stakeholders (owners, designers, and operators). The Laboratory Benchmarking Tool can be used to document and track metrics over the project's life cycle.

References

CEC (2018, December). California Energy Commission: 2019 Building Energy Efficiency Standards for Residential and Nonresidential Buildings. CEC-400-2018-020-CMF. Retrieved from https://ww2.energy.ca.gov/publications/displayOneReport_cms.php?pubNum=CEC-400-2018-020-CMF.

ENERGY STAR/EPA (2019, August). Source Energy: ENERGY STAR Portfolio Manager Technical Reference. Retrieved from https://portfoliomanager.energystar.gov/pdf/reference/Source%20Energy.pdf.

EPA (2012, October). WaterSense at Work. Retrieved from https://www.epa.gov/sites/production/files/2017-01/documents/ws-commercial-water-sense-at-work-ci.pdf.

FEMP (n.d.). Federal Laws and Requirements Search: High Performance Sustainable Buildings. Retrieved from https://www4.eere.energy.gov/femp/requirements/requirements_filtering/specialty_facilities.

Frenze, D., Greenberg, S., Mathew, P., Sartor, D., & Starr, W. (2005, August) Laboratories for the 21st Century: Rightsizing Laboratory Equipment Loads. Retrieved from https://www.i2sl.org/documents/toolkit/bp_rightsizing_508.pdf.

Gudorf, M., & Hartley, C. (2013). Measured Equipment Load – Is this a Good Metric for Lab Design? I^{2}SL Annual Conference presentation.

I^{2}SL (n.d.) SmartLabs Toolkit. Retrieved from https://smartlabs.i2sl.org/index.html.

I^{2}SL (2020). Laboratory Benchmarking Tool. Retrieved from https://lbt.i2sl.org/.

I^{2}SL (2020). ASHRAE 90.1-2019 Appendix G Lab Modeling Guidelines. International Institute for Sustainable Laboratories. Retrieved from https://www.i2sl.org/documents/resources/laboratorybuildingenergymodelingguideline_2019.pdf.

Mathew, P. (2007, December). Peak Laboratory Equipment Loads. *HPAC Engineering*.

NBI (n.d.). zero Energy Performance Index. New Buildings Institute. Retrieved from https://newbuildings.org/code_policy/zepi/.

SB2030 (n.d.). B3 Sustainable Building 2030 Energy Standards. Retrieved from https://www.b3mn.org/2030energystandard/.

Tanner, S. (2005, May) Laboratories for the 21st Century: Water Efficiency Guide for Laboratories. Retrieved from https://www.i2sl.org/documents/toolkit/bp_water_508.pdf.

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Appendix A: Expanded List of Metrics

This list included the priority metrics as well as additional metrics that could be used depending on project goals, stakeholder interests and priorities.

Metric: ● More Relevant ○ Less Relevant	Priority	New Construction	Existing Building
Whole Building			
Site energy use intensity [kBtu/sf/yr ; kWh/sqm/yr]	High	●	●
Source energy use intensity [kBtu/sf/yr ; kWh/sqm/yr]	High	●	●
Building purchased energy cost intensity [$/sf-yr ; S/sqm/yr]	Low	●	●
Building peak electrical load intensity [peak W/sf]	Med	●	●
Greenhouse gas intensity [lbs CO_2e/sf/yr ; kg CO_2e/sqm/yr]	High	●	●
Potable water use intensity [gal/sf/yr ; l/sqm/yr]	High	●	●
Total water use intensity [gal/sf/yr ; l/sqm/yr]	Med	●	●
Renewable energy intensity [kBtu/sf/yr ; kWh/sqm/yr]	Low	●	●
Embodied carbon intensity [$MTCO_2$e/sf]	Low	●	○
Ventilation System			
Minimum ventilation rate (volume) [ACH]	High	●	●
Minimum ventilation rate (area) [cfm/sf ; l/s/sqm]	High	●	●
Airflow efficiency [W/cfm ; W/l/s]	High	●	○
System pressure drop [in.w.g. ; Pa]	High	●	○
Fume hood airflow ratio [-]	High	○	●
All exposure control devices airflow ratio [-]	Med	○	●
Fume hood face velocity [ft/min]	Med	○	●
Ventilation energy use intensity [kWh/sf-yr ; kWh/sqm/yr]]	Med	●	●
Fume hood density [ft/sf ; m/sqm]	Low	●	○
Cooling and Heating			
Lab temperature deadband [F ; C]	Med	○	●
Lab humidity deadband [%]	Med	○	●
Cooling system efficiency [kW/ton ; kWe/kWt]	High	●	●

Metric: ● More Relevant ○ Less Relevant	Priority	New Construction	Existing Building
Chiller rated efficiency [NPLV kW/ton]	Med	●	●
Cooling system energy use intensity [kWh/sf-yr ; kWh/sqm/yr]	Med	●	●
Chiller system minimum turndown ratio [-]	Low	○	●
Cooling tower efficiency [kW/ton ; kWe/kWt]	Low	●	●
Cooling tower approach [F, C]	Low	○	●
Chilled water pumping efficiency [W/gpm ; W/l/s]	Low	●	●
Condenser water pumping efficiency [W/gpm ; W/l/s]	Low	●	●
Chilled water loop temperature differential [F ; C]	Low	○	●
Heating system efficiency [%]	High	●	●
Boiler rated efficiency [%]	Med	●	●
Heating energy use intensity [kBtu/sf-yr ; kWh/sqm/yr]	Med	●	●
Reheat energy use factor (reheat kBtu/space heat kBtu) [%]	Low	○	●
Plug loads			
Laboratory peak plug load intensity [W/sf ; W/sqm]	High	●	○
Laboratory average plug load intensity - measured [W/sf ; W/sqm]	High	○	●
Plug load energy use intensity [kWh/sf-yr ; kWh/sqm/yr]	Med	●	●
Lighting			
Installed laboratory lighting power density [W/sf ; W/sqm]	High	●	○
Laboratory task illuminance setpoint [fc ; lux]	Med	●	●
Laboratory ambient illuminance setpoint [fc : lux]	Med	●	●
Lamp+ballast efficacy [lm/W ; lux/W]	Med	●	○
Color rendition index	Low	●	○
Daylight glare probability	Low	●	○
Lighting energy use intensity [kWh/sf-yr ; kWh/sqm/yr]	Med	●	●